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Forced oscillator model of dynamic spatial charge field in the reduced Zn:Fe:$LiNbO_3$ crystal

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ABSTRACT

Holographic data storage is promised to be the next-generation optical storage technology for many years. The Zn:Fe:$LiNbO_3$ crystal is studied widely because of its promising holographic storage properties. The forced oscillator model is used to explain the self-erasing phenomenon in the reduced Zn:Fe:$LiNbO_3$ crystals. It is showed that the total spatial charge field is dominated by two kinds of carrier with different respond time, which are electron and hole, respectively. The cooperative action of two kinds carrier induces that the total charge field non-monotonically varies with the recording time. The same diffraction efficiency of hologram with equal exposure energy is realized by the self-erasing property. The precision of the optical correlation recognition based on holographic storage will be improved.

1. Introduction

Holographic date storage is promised to be the next-generation optical storage technology for many years [1,2]. However, its commercial application is resisted by lacking of ideal medium.

The congruent Lithium niobate ($LiNbO_3$) doped Fe ions is the most promising optical data storage material because of its high diffraction efficiency and photo-refractive sensitivity. But long response time and strong scattering noise limit its applications [3,4]. Although some techniques have been used to suppress the noise [5,6], the most essential way is to optimize the properties of crystal itself through doping with damage-resistant dopants, such as Zn^{2+}, Mg^{2+}, In^{3+}, etc. [7–9].

The Zn:Fe:$LiNbO_3$ crystal has been widely studied since 1990s because of its high response rate and strong the ability of optical damage resistance [10]. The self-erasing phenomenon, which is the spatial charge field grows gradually to its maximum and then decays a great extent during the recording process, has been found in the reduced Zn:Fe:$LiNbO_3$ crystal [11].

In this paper, the forced oscillator model is used to explain self-erasing phenomenon. And the self-erasing property is used to realize same diffraction efficiency of hologram. It is helpful to improve the precision of the optical correlation recognition based on holographic storage.

2. Forced oscillator model of spatial charge field

In recording process, the dynamic spatial charge field can be described by the group equation as followed [12].

$$\frac{\partial n}{\partial t} = \frac{\partial N_D^+}{\partial t} + \frac{1}{q}\nabla \cdot \vec{J} \tag{1}$$

$$\frac{\partial N_D^+}{\partial t} = (sI + \beta)(N_D - N_D^+) - \gamma_R N_D^+ n \tag{2}$$

$$\vec{J} = qD\nabla n + q\mu n\vec{E} + \vec{J}_{ph} \tag{3}$$

$$\nabla \cdot (\varepsilon\vec{E}) = q(N_D^+ - N_A - n) \tag{4}$$

where n, N_D and N_A are density of electron, acceptor and donor, respectively. N_D^+ is density of ionized donors, $\vec{J}$ is current density, $\vec{E}$ is total intensity of electric field which included spatial charge-field and applied field, I is intensity of incident light, q is electric quantity, β is thermal-excitation rate, s is light excitation cross section of donor, γ_R is recombination constant, μ is mobility of charge migration, D is diffusion coefficient, T is absolute temperature, $\vec{J}_{ph}$ is density of photovoltaic current, ε is dielectric coefficient, t is time.

The influence of photovoltaic electric field E_{ph} on mobility of charge carrier must be noticed in $LiNbO_3$ crystal. The spatial charge-field which is generated by photovoltaic effect is similar with applied field. So the photovoltaic electric field E_{ph} can be regarded as the applied direct field E_0 along c axis. In formula (3), if E is the summation of applied field and photovoltaic field, the

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density of photovoltaic current can be ignored. The formula (3) can be described as

$$\vec{J} = qD\nabla n + q\mu n\vec{E} \tag{5}$$

Some assumption is used to simply problem: (1) The change of all physical parameter is one dimension, that is $\nabla = (\partial/\partial x)i_x$. (2) $\beta \ll sI$, the thermal excitation of carrier is ignored. (3) The dielectric coefficient, $\varepsilon = \varepsilon_0\varepsilon_r$, is a constant.

The time derivates of the formula (4) is calculated, and then is substituted for formula (4) and (2), the result is

$$\frac{\partial^2 E}{\partial t\partial x} + (sI + \gamma_R n)\frac{\partial E}{\partial x} + \frac{q}{\varepsilon}\frac{\partial n}{\partial t} + \frac{q}{\varepsilon}(sI + \gamma_R n + \gamma_R N_A)n + \frac{q}{\varepsilon}[N_A - N_D]sI = 0 \tag{6}$$

The result of derivates of the formula (4) with respect to x is substituted into the formula (1), and then N_D^+ is eliminated. The result is

$$\frac{\partial n}{\partial t} - D\frac{\partial^2 n}{\partial x^2} - \mu E\frac{\partial n}{\partial x} + \left[\frac{\varepsilon}{q}sI + \frac{\varepsilon}{q}\gamma_R n - \mu n\right]\frac{\partial E}{\partial x} + (sI + \gamma_R n + \gamma_R N_A)n + [N_A - N_D]sI = 0 \tag{7}$$

The modulation of incident light is a function described as

$$I = I_0(1 + m\cos kx) = I_0 + I_0\left[\frac{m}{2}\exp(ikx) + \frac{m}{2}\exp(-ikx)\right] \tag{8}$$

where m is modulation of light intensity, $k = 2\pi/\Lambda$ is grating wavenumber, $I_0 = I_1 + I_2$ is total intensity of incident light. In the process of recording grating, the density of electron and the electric field are modulated by incident light. So their spatial distribution can be regarded as that of the intensity of incident light.

$$n = n_0 + \left[\frac{n_1(t)}{2}\exp(ikx) + \frac{n_1(t)}{2}\exp(-ikx)\right] \tag{9}$$

$$E = E_0 + \left[\frac{E_1(t)}{2}\exp(ikx) + \frac{E_1(t)}{2}\exp(-ikx)\right] \tag{10}$$

Eqs. (8), (9) and (10) are substituted into Eqs. (6) and (7). The physical parameters with footnote 1 are less than parameters with footnote 0. The parameters with footnote 0 and 1 in two sides of the equation are equal, and then the high order parameters can be ignored, so

$$n_0 = \frac{sI_0(N_D - N_A)}{sI_0 + \gamma_R n_0 + \gamma_R N_A} \tag{11}$$

$$\frac{dn_1}{dt} + n_1(sI_0 + 2\gamma_R n_0 + \gamma_R N_A) + ik\frac{\varepsilon}{q}\frac{dE_1}{dt} + ik\frac{\varepsilon}{q}(sI_0 + \gamma_R n_0)E_1 + smI_0(n_0 + N_A - N_D) = 0 \tag{12}$$

$$\frac{dn_1}{dt} + n_1(Dk^2 - ik\mu E_0 + sI_0 + 2\gamma_R n_0 + \gamma_R N_A) + ikE_1\left[\frac{\varepsilon}{q}(sI_0 + \gamma_R n_0) - \mu n_0\right] + smI_0(n_0 + N_A - N_D) = 0 \tag{13}$$

Eq. (13) minus (12), that is

$$n_1 = \left(\frac{ik(\varepsilon/q)}{Dk^2 - ik\mu E_0}\right)\frac{dE_1}{dt} + \left(\frac{ik\mu n_0}{Dk^2 - ik\mu E_0}\right)E_1 \tag{14}$$

The time derivative of Eq. (14) is put into Eq. (13),

$$\frac{d^2E_1}{dt^2} + \left[(sI_0 + 2\gamma_R n_0 + \gamma_R N_A) + (Dk^2 - ik\mu E_0) + \mu n_0\frac{q}{\varepsilon}\right]\frac{dE_1}{dt} + \left\{[Dk^2 - ik\mu E_0][sI_0 + \gamma_R n_0] + [sI_0 + 2\gamma_R n_0 + \gamma_R N_A]\mu n_0\frac{q}{\varepsilon}\right\}E_1 = -smI_0[k\mu E + iDk^2](N_D - N_A - n_0)k\frac{q}{\varepsilon} \tag{15}$$

Where they are defined as

$$\gamma = [sI_0 + 2\gamma_R n_0 + \gamma_R N_A] + [Dk^2 - ik\mu E_0] + [\mu n_0 q/\varepsilon] \tag{16}$$

$$\omega_0^2 = [Dk^2 - ik\mu E_0][sI_0 + \gamma_R n_0] + [sI_0 + 2\gamma_R n_0 + \gamma_R N_A][\mu n_0 q/\varepsilon] \tag{17}$$

$$f = -smI_0[k\mu E + iDk^2](N_D - N_A - n_0)q/\varepsilon k \tag{18}$$

Eq. (15) can be described as

$$\frac{d^2E_1}{dt^2} + \gamma\frac{dE_1}{dt} + \omega_0^2 E_1 = f \tag{19}$$

The form of Eq. (19) is defined as the force oscillator equation. Where γ is regarded as complex damp coefficient of material, ω_0 is complex natural frequency, f is the driver force which depends upon the intensity of incident light. The action of spatial charge-field is similar with the force oscillator.

3. Double exponent evolution of spatial charge field versus recording time

As we known, the modulation of refractive index and spatial charge-field as n_1 and E_1 is zero at $t = 0$, that is

$$n_1|_{t=0} = 0\, E_1\big|_{t=0} = 0 \tag{20}$$

(20) is substituted for (14),

$$\frac{dE_1}{dt}\bigg|_{t=0} = 0 \tag{21}$$

The formula (20) and (21) are regarded as the initial condition of Eq. (19). So the general solution of (19) can be obtained.

$$E_1 = E_{sc}^0\left[1 - \left(\frac{c_2}{c_2 - c_1}\right)\exp(c_1 t) - \left(\frac{-c_1}{c_2 - c_1}\right)\exp(c_2 t)\right] \tag{22}$$

where $E_{sc}^0 = (f/\omega_0^2)$ is static spatial charge-field, $c_1 = -\gamma + \sqrt{\gamma^2 - 4\omega_0^2}/2$ and $c_2 = -\gamma - \sqrt{\gamma^2 - 4\omega_0^2}/2$. The formula (22) indicates that the spatial charge-field varies as double-exponentially versus recording time in $LiNbO_3$ crystal, and there are two respond time $\tau_{sc1} = -1/c_1$ and $\tau_{sc2} = -1/c_2$, respectively.

If $c_1/c_2 \ll 1$, then the formula (22) can be transformed as

$$E_1 = E_{sc}^0\left[1 - \left(\frac{1}{1 - c_1/c_2}\right)\exp(c_1 t) - \left(\frac{-c_1/c_2}{1 - c_1/c_2}\right)\exp(c_2 t)\right] \approx E_{sc}^0\left[1 - \exp(c_1 t) + \frac{c_1}{c_2}\exp(c_2 t)\right] \approx E_{sc}^0[1 - \exp(c_1 t)] \tag{23}$$

This result is consistent with the exponent form of spatial charge-field described as reference [9,10]. If $c_1 > c_2$ or $c_1 \approx c_2$, spatial charge-field varies double-exponentially with recording time.

The formula (23) indicates that the spatial static charge-field in $LiNbO_3$ crystal is due to light intensity and complex natural frequency of crystal lattice. And then the respond time of grating depends on the fixed carrier.